DYNAMICS OF ERROR BACKPROPAGATION LEARNING WITH PRUNING IN THE WEIGHT SPACE

Andrzej Lozowski, Damon A. Miller, and Jacek M. Zurada

Department of Electrical Engineering, University of Louisville
Louisville, Kentucky 40292
e-mail: jmzura02@starbase.spd.louisville.edu

ABSTRACT

Structural learning as proposed by Ishikawa [1] has had success in reducing unimportant weights in an initially oversized multilayer feedforward neural network during training. This technique employs a forgetting constant ε which determines the rate of weight decay during learning. A formalization of this method is obtained by considering the weights as the states of a dynamic system. Analysis of the system eigenvalues and simulation indicate that ε controls removal of fixed points corresponding to the weights of oversized networks. Thus considering error backpropagation as a dynamic system has enabled analysis of structural learning.

1. INTRODUCTION

Structural learning of feedforward neural networks offers effective pruning with a relatively simple learning rule [1]. This learning rule includes a term which forces weights to decay during training. Near minimal networks can be obtained by applying this rule to initially oversized networks. Many of the weights are typically small at the conclusion of training, and thus both weights and neurons may be subsequently pruned. Although the structural learning rule with its forgetting constant is well understood intuitively, the choice of a specific value of the constant is somewhat arbitrary [2].

In order to analyze the structural learning, the learning must be expressed more formally. Based on a given training set the error backpropagation (EBP) algorithm moves the weights from some random initial condition towards the final value corresponding to the closest local minimum of an error function. The fact that during learning the weights evolve in time while the training set remains invariant suggests that the network weights can be considered as states of a dynamic system [3].

The objective of this paper is to characterize solutions which correspond to fixed points in the weight space in terms of their stability with respect to the forgetting constant, which is considered to be a parameter of the learning dynamics. It will be shown that this parameter controls the eigenvalues of the fixed points [4] and hence their convergence properties. Thus the forgetting constant determines the number of stable fixed points in the weight space. The best pruning occurs when all the solutions corresponding to oversized networks are removed from the weight space by training with an appropriate forgetting constant. These solutions become unreachable from any initial condition.

2. EBP LEARNING AS A DYNAMIC SYSTEM

Assume that $\vec{w}$ is a vector composed of the neural network weights. Considering backpropagation learning as a dynamic system, the weight vector $\vec{w}$ is understood to be the state of this system. The standard EBP learning rule [5] is a discrete time mapping from $\vec{w}_n$ to $\vec{w}_{n+1}$ given by

$$\vec{w}_{n+1} = \vec{w}_n - \eta \frac{dE(\vec{w}_n)}{d\vec{w}_n}, \tag{1}$$

where $E(\vec{w})$ is the error function for a given training set. More specifically, $E(\vec{w})$ is a functional defined at each state $\vec{w}$ which can be interpreted as the state potential in the weight space. Starting from some initial condition $\vec{w}_0$ the dynamic rule (1) determines the cascade trajectory $\{\vec{w}_n\}$ which leads to the nearest local minimum of the functional E. The minimum is located at a fixed point $\vec{w}_F$ which is an attractor of the trajectory $\{\vec{w}_n\}$.

As $\eta \to 0$ the discrete-time dynamic system with rule (1) becomes an approximation of a continuous-time dynamic system described by the differential equation [6]

$$\frac{d\vec{w}(t)}{dt} = \vec{F}(\vec{w}), \qquad \vec{w}(0) = \vec{w}_0, \tag{2}$$

where the vector function is defined as $\vec{F}(\vec{w}) = -dE(\vec{w})/d\vec{w}$. Thus the derivative of the state is proproportional to the gradient of the potential function $E(\vec{w})$ with a negative proportionality coefficient. Tra-

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jectory $\vec{w}(t)$ is a continuous manifold in the weight space, leading from the initial condition $\vec{w}_0$, passing through points $\{\vec{w}_n\}$, and eventually ending at an attractor $\vec{w}_F$.

Ishikawa suggested [1] a modification of equation (1) to force the weights to decay during learning. Expressing Ishikawa's structural learning with a continuous-time dynamic rule as proposed yields

$$\frac{dw_{ij}^s}{dt} = -\frac{\partial E}{\partial w_{ij}^s} - \varepsilon \operatorname{sign} w_{ij}^s. \tag{3}$$

Here w_{ij}^s is an entry in weight vector $\vec{w}$ corresponding to the weight connecting the j-th neuron from the layer preceding the s-th layer (or input) with the i-th neuron from the s-th layer. Intuitively, the first term in rule (3) moves state $\vec{w}$ to minimize the original EBP functional E while the second term forces weight decay. As a result of these two conflicting criteria both learning and weight decay occur—some of the weights are suppressed to zero while the remaining weights are responsible for the error minimization. The parameter ε controls the level of pruning.

More formally, the pruning effect can be explained in terms of the stability of the fixed points created in the weight space by equation (3). The new locations of the fixed points is determined by the modified potential function $E_\varepsilon(\vec{w}) = \int \vec{F}_\varepsilon(\vec{w})d\vec{w}$. To enable integration the signum function on the right side of equation (3) can be approximated as $\operatorname{sign}(w_{ij}) \approx \tanh(\beta w_{ij})$ with β sufficiently large. Thus the smoothed dynamic rule reads

$$\frac{d\vec{w}(t)}{dt} = \vec{F}_\varepsilon(\vec{w}) = -\frac{dE_\varepsilon(\vec{w})}{d\vec{w}} - \varepsilon \tanh(\beta\vec{w}). \tag{4}$$

The location of fixed points in the weight space can be determined by setting the time derivatives of state $\vec{w}$ as in (4) to zero. Thus the fixed point equation is

$$\vec{F}_\varepsilon(\vec{w}_F) = \vec{0}. \tag{5}$$

In order to determine the stability of the fixed point $\vec{w}_F$, $\vec{F}_\varepsilon$ can be linearized in the neighborhood $\vec{w}_F + \Delta\vec{w}$, yielding

$$\frac{d}{dt}\Delta\vec{w} \approx \left.\frac{d\vec{F}_\varepsilon(\vec{w})}{d\vec{w}}\right|_{\vec{w}=\vec{w}_F} \Delta\vec{w}. \tag{6}$$

The stability of the fixed point $\vec{w}_F$ depends upon the convergence properties of its neighborhood. The fixed point is an attractor if all the eigenvalues of the Jacobian $J_\varepsilon(\vec{w}_F) = d\vec{F}_\varepsilon(\vec{w})/d\vec{w}$ evaluated at $\vec{w} = \vec{w}_F$ are non-positive real numbers. Let λ_{max} be the maximum eigenvalue of the Jacobian $J_\varepsilon(\vec{w}_F)$. As long as λ_{max} is non-positive, the trajectory $\Delta\vec{w}(t) = \Delta\vec{w}_0 \exp(J_\varepsilon(\vec{w}_F)t)$, starting from an initial state $\Delta\vec{w}_0$, converges to the fixed point $\vec{w}_F$. If λ_{max} is positive, the trajectory departs from $\vec{w}_F$ in the direction of the eigenvector corresponding to that eigenvalue. Thus, only fixed points with non-positive λ_{max} should be considered as attractors in the weight space of the neural network during learning. Unstable fixed points are not reachable from any initial condition $\vec{w}_0$ except for those located exactly at separatrices of $\vec{w}_F$.

We may therefore group the system eigenvalues at the fixed point into two classes, namely those which are negative and those which are zero. Negative eigenvalues are responsible for the attracting directions in the weight space. Zero eigenvalues indicate directions in which movement of the weights does not affect the potential functional. Zero-valued eigenvalues effectively reduce the order of the system.

Note that system (4) is parameterized with a forgetting rate ε [4]. For $\varepsilon = 0$, the dynamic system represents standard EBP, and thus there may be many stable fixed points, representing the many possible solutions of the learning process. For a large value of ε, the second term in equation (4) dominates the first term, and the system simplifies to a set of first order independent differential equations. Furthermore, this system is linear except in a small region around the origin of the weight space. The only fixed point for the case of large ε is the origin of the weight space. Here the system Jacobian $J_\varepsilon(\vec{w}_F)$ has non-zero entries only along the diagonal, and these entries are proportional to $-\varepsilon$.

Thus ε affects the stability of fixed points. Specifically, if λ_{max} of a fixed point is negative but close to zero, changing ε may cause this eigenvalue to become positive. This makes the fixed point unstable and eliminates it from the weight space as a solution of the learning process. Hence, learning with various forgetting rates ε results in a different density of stable fixed points $\vec{w}_F$. The question arises as to how the forgetting rate is related to the density of these fixed points and why certain values of ε are recommended for the best pruning results[2]. The sensitivity of λ_{max} to changes of ε at the fixed points is crucial for answering this question.

Consider that equation (4) is a dynamic rule of learning with parameter ε. Therefore a given fixed point is a function of this parameter: $\vec{w}_F = \vec{w}_F(\varepsilon)$. Taking into account the fixed point equation (5), the movement of the fixed point $\vec{w}_F$ with respect to ε can be approxi-

mated as

$$\frac{d\vec{w}_F}{d\varepsilon} = \left(\frac{\partial \vec{F}_\varepsilon(\vec{w}_F)}{\partial \vec{w}_F}\right)^{-1} \frac{\partial \vec{F}_\varepsilon(\vec{w}_F)}{\partial \varepsilon}. \qquad (7)$$

For a small change $\Delta\varepsilon$ the fixed point moves from $\vec{w}_F$ to the new location $\vec{w}'_F$. As a result of this movement the new fixed point has new convergence properties.

3. NUMERICAL RESULTS

In order to demonstrate the relation between the eigenvalues of fixed points in the weight space and the parameter ε, system (4) was simulated for the case of block training a 3-5-1 multilayer feedforward network for the XOR problem. The desired outputs for the network were either ± 0.9 to allow the neurons to reach the desired output states. The system was intialized to a random initial condition $\vec{w}_0$ and allowed to evolve in time to a fixed point. Once at the fixed point, ε was perturbed, and the system was again brought into equilibrium. For each new position of the fixed point, the system eigenvalues were evaluated. Figure 1 shows the system eigenvalues for a fixed point as it moves with changes of ε. Note that at $\varepsilon = 0$ both non-zero and zero eigenvalues exist, but with an increase in ε the system becomes full order.

Figure 2 shows the maximum system eigenvalue as ε is varied. Note that the fixed point becomes more stable up to a critical value of ε, where the stability of the fixed point starts to decrease. A further increase of ε causes this fixed point to become unstable, forcing the system to another fixed point, which in this case is the origin. This state transition is indicated by the discontinuous jump to the second distinct part of the curve, which corresponds to the convergence properties of the origin.

Figure 3 shows the error of the learning process for the same fixed points. Note that for $\varepsilon = 0$, the error is essentially zero, in contrast to typical solutions from EBP, since EBP utilizes the first order Euler method, which is only asymptotically convergent to fixed points. For non-zero values of ε, this dynamic approach resulted in weights which were either strongly non-zero or practically identical to 0, as opposed to a situation for EBP structural learning, for which some of the weights may be close to zero, but far enough from 0 to cause hesitation at their removal during pruning. Again, since we are considering fixed points, solutions may no longer decay, and thus weights unimportant to the system mapping must be definitively zero. Note that this graph also reflects the increase of error inherent in the balancing of the contradictory goals of error and complexity minimization.

In Figure 4 the eigenvalues of the fixed point at the origin are shown. With $\varepsilon = 0$ the origin is not stable as most of the eigenvalues are 0. The one non-zero eigenvalue corresponds to the weight connected to the hidden layer bias neuron. This plot demonstrates that the system eigenvalues at the origin are proportional to ε.

4. CONCLUSIONS

The ability of structural learning to reduce the magnitude of weights of a multilayer feedforward neural network has been analyzed by considering the forgetting rate ε as a parameter of a dynamic system. ε controls the convergence properties of fixed points in the weight space which correspond to solutions of the learning process. Furthermore, results indicate that the dynamic system approach offers the ability to determine the final result of error backpropagation training, and thus this formalization will hopefully enable analysis of not only structural learning but also other training methodologies.

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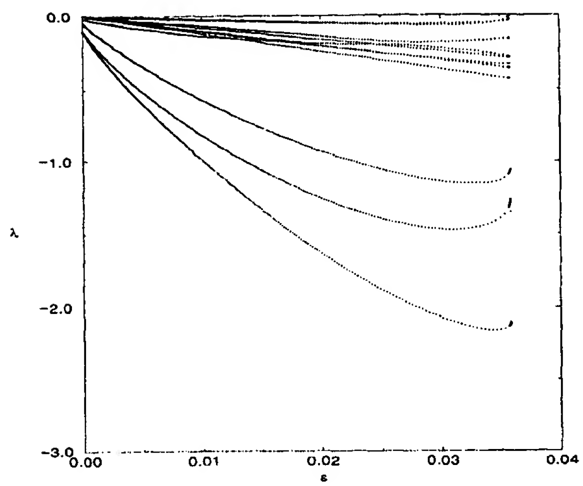

Figure 1. System eigenvalues for a fixed point as ε is varied.

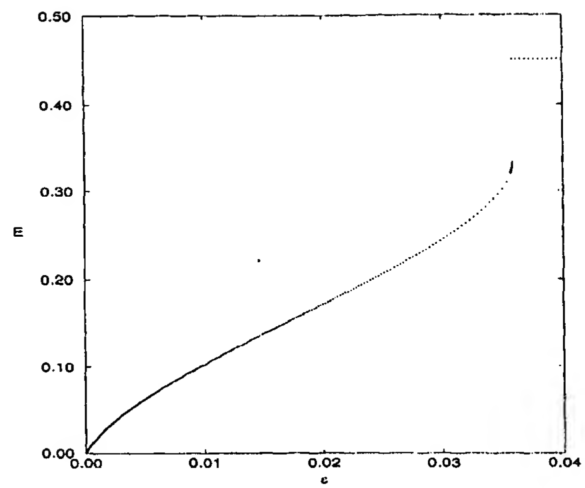

Figure 3. Network output error for two fixed points as ε is varied.

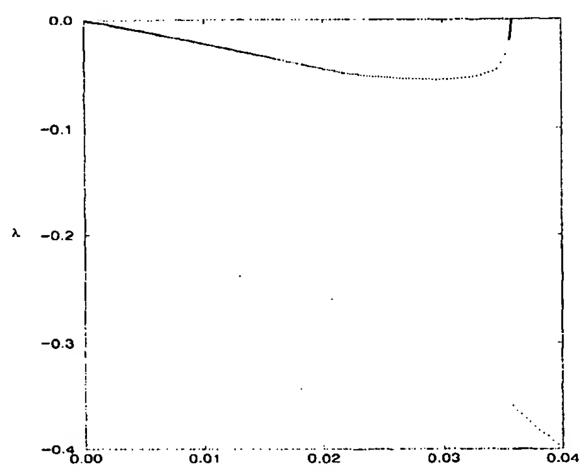

Figure 2. Maximum system eigenvalue for two fixed points as ε is varied.

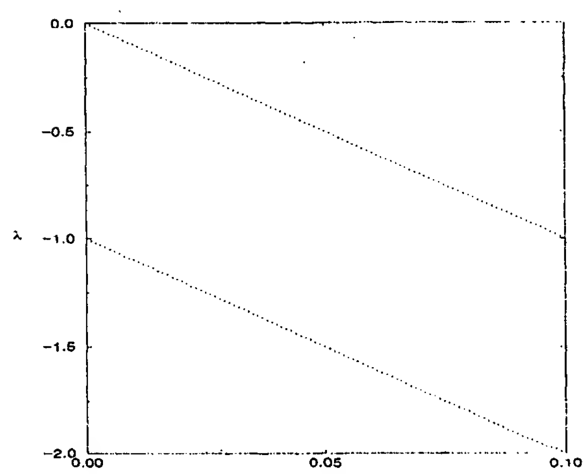

Figure 4. Eigenvalues at the origin of the weight space as ε is varied.

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Sampson, R.D.; Peterson, A.E.; Lozowski, E.P.;
Electrical and Computer Engineering, 1999 IEEE Canadian Conference on , Volume: 2 , 1999
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16 **Commissioning and future plans for polarized protons in RHIC**
Mackay, W.W.; Ahrens, L.; Bai, M.; Bunce, G.; Courant, E.; Deshpande, A.; Drees, A.; Fischer, W.; Huang, H.; Kurita, K.; Luccio, A.U.; Makdisi, Y.; Pilat, F.; Ptitsin, V.; Roser, T.; Saito, N.; Satogata, T.; Tepikian, S.; Trbojevic, D.; Tsoupas, N.; van Z
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19 **Bifurcati n-based neural c mputati n**
Lysetskiy, M.; Zurada, J.M.; Lozowski, A.;
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20 **Complex-valued multistate neural associative memory**
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21 **Measurement of dielectrics at 100 GHz with an open resonator connected to a network analyzer**
Hirvonen, T.M.; Vainikainen, P.; Lozowski, A.; Raisanen, A.V.;
Instrumentation and Measurement, IEEE Transactions on , Volume: 45 Issue: 4 , Aug 1996
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22 **Brushing up on your maintenance practices**
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[Abstract] [PDF Full-Text (3812 KB)] **IEEE JNL**

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Zurada, J.M.; Lozowski, A.; Malinowski, A.;
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[Abstract] [PDF Full-Text (496 KB)] **IEEE CNF**

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